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**SR-52 Programmable Calculator
Programs for Venturi Scrubbers and
Electrostatic Precipitators**

Industrial Environmental Research Lab, Research Triangle Pk., NC

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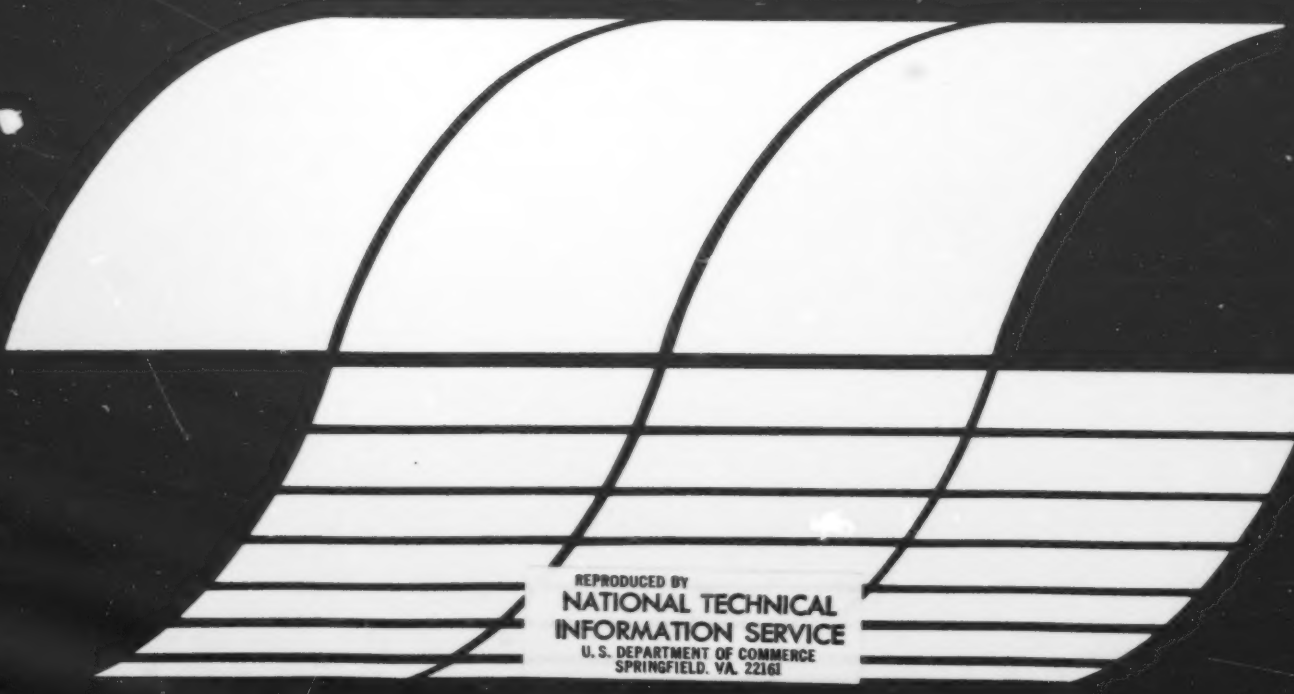
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SR-52 PROGRAMMABLE CALCULATOR PROGRAMS FOR VENTURI SCRUBBERS AND ELECTROSTATIC PRECIPITATORS

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Program Report



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by

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ABSTRACT

This report is intended to provide useful tools for estimating particulate removal by venturi scrubbers and electrostatic precipitators. Detailed descriptions are given for programs to predict the penetration (1 minus efficiency) for each device. These programs are written specifically for the Texas Instruments SR-52 programmable calculator. Each program includes a general description of the mathematical model upon which the program is based and the formulas and numerical techniques used in adapting the model to the SR-52. Numerical examples, program listing, and user instructions are included.

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NOMENCLATURE

A	-	Collector plate area in electrostatic precipitator (ESP)
a	-	First curve fit parameter for $w(d) = a + bd + cd^2$
B	-	Correction factor sneakage and reentrainment in ESP
b	-	Second curve fit parameter for $w(d) = a + bd + cd^2$
C'	-	Cunningham correction factor
c	-	Third curve fit parameter for $w(d) = a + bd + cd^2$
D	-	Drop diameter
d	-	Particle diameter
d_i	-	Initial particle diameter for integration
d_f	-	Final particle diameter for integration
d_g	-	Mass mean particle diameter
E_o	-	Overall collection efficiency
E_p	-	Electric field at plate
F	-	Correction factor for non-uniform gas flow in ESP
f	-	Empirical factor in scrubber model
$f(d)$	-	Fraction of particles with diameters between d and d + dd
j	-	Current density
K_1, K_2	-	Constants used in scrubber program
K_{pt}	-	Inertial impaction parameter evaluated at throat of venturi scrubber
L/G	-	Non-dimensional liquid/gas flow rate ratio for venturi scrubber
N_s	-	Number of baffled sections in ESP
h	-	Number of steps in numerical integration
$Pt(d)$	-	Penetration (1 minus efficiency) of particles of diameter d
$Pt'(d)$	-	Corrected penetration of particles of diameter d used in ESP model
Pt_o	-	Overall particle penetration

q	-	Particle electrical charge
R_{ij}	-	Storage register ij
S	-	Fraction of particles that are reentrained and that bypass electrified region per section
T	-	Temperature
u_G	-	Gas velocity
V	-	Volumetric flow rate of gas
$w(d)$	-	Electrical migration velocity of particles with diameter d
Δd	-	Particle diameter increment for numerical integration
Δp	-	Pressure drop
μ	-	Gas viscosity
ρ	-	Dust electrical resistivity
ρ_L	-	Liquid density
ρ_p	-	Particle density
σ	-	Normalized standard deviation of gas flow
σ_g	-	Geometric standard deviation of log normal size distribution

INTRODUCTION

Computer models for particle collection in venturi scrubbers¹ and electrostatic precipitators² have been developed under EPA sponsorship. These models, which are fully described in referenced reports, provide useful tools for the design, specification, selection, and troubleshooting of particulate control devices.

Recent advances in calculator technology make it possible to use these models without a large computer. The scrubber model described by Calvert et al.¹ has been fully programmed for a Texas Instruments SR-52 programmable calculator. Results of calculations made with the ESP computer model described by Gooch et al.² have been incorporated in an SR-52 program which has much of the power and usefulness of the full computer model.

These SR-52 programs and examples of their use are presented in this report. These programs are written for the SR-52 and the PC-100A printer. Instructions on how to use the programs without the printer are also presented.

Typical uses of the SR-52 programs are presented in the example problems. Several examples for both the scrubber and the ESP program are presented to enable the user to get a "feel" for the programs before he tries to solve his own problems.

NOTES ON THE PROGRAMS

In the user instructions and examples, a convention of underline letters or numbers has been adopted to denote the key or keys on the SR-52 keyboard which should be pressed to conduct the operation discussed. For example: in the instruction Press A, the underline indicates that the A button on the keyboard should be pressed. Storage registers are indicated by R_{ij} . For example: R_{01} refers to storage register 01.

The programs all make extensive use of the indirect recall and indirect store features of the SR-52. Thus, it is essential that the counter for the indirect recall and indirect store register be set at the proper initial value and advanced at the required times. Anyone who wishes to modify the programs should remember that the programs as written depend on indirect recall and indirect store instructions.

Cards are entered into the SR-52 calculator by:

<u>Step</u>	<u>Procedure</u>	<u>Press</u>
1	Enter side A	<u>2nd</u> <u>rst</u> <u>2nd</u> <u>read</u>
2	Enter side B	<u>2nd</u> <u>read</u>

In the program listing, the use of the 2nd key is denoted by asterisk. Thus, the notation, for example, B'^* means press 2nd B'.

VENTURI SCRUBBER

MATHEMATICAL MODEL

The mathematical model used in the SR-52 program was developed by Calvert and is fully described by Calvert et al.¹ Therefore, only a brief discussion of the model will be given here.

The mathematical model of a venturi scrubber consists of two parts: one to predict scrubber pressure drop; the other to predict scrubber particle collection efficiency.

Scrubber Pressure Drop

Pressure drop in a venturi scrubber is caused by acceleration and by wall friction. The pressure drop due to acceleration is generally the larger. Therefore, pressure drop due to wall friction will be neglected.

The pressure drop due to acceleration is reasonably insensitive to scrubber geometry and can be predicted from hydrodynamics. Calvert³ derived the following equation for venturi scrubber pressure drop:

$$\Delta p \text{ (cm water)} = 1.03 \times 10^{-3} [u_G (\frac{\text{cm}}{\text{sec}})]^2 \frac{L}{G} \quad (1)$$

where u_G is the gas velocity in the venturi throat, and L/G is the dimensionless liquid to gas flow rate ratio.

Calvert et al.⁴ have compared the predictions of equation (1) with experimental data and concluded that the equation consistently overpredicts pressure drop in a venturi scrubber by about 20%. They suggest that equation (2) below gives better agreement with the data.

$$\Delta p \text{ (cm water)} = 8.24 \times 10^{-4} [u_G \left(\frac{\text{cm}}{\text{sec}} \right)]^2 \frac{L}{G} \quad (2)$$

Equation (2) is the equation used to predict pressure drop in the SR-52 model.

Particle Penetration

The overall particle penetration (1 minus efficiency) through a venturi scrubber is given by:

$$Pt_0 = \int_0^\infty Pt(d)f(d)dd \quad (3)$$

where Pt_0 is the overall particle penetration, $Pt(d)$ is the penetration of particles with diameter d , and $f(d)$ the fraction of particles with diameters between d and $d + dd$.

Calvert et al.¹ derived equation (4) for $Pt(d)$:

$$Pt(d) = \exp \left[\frac{2}{55} \frac{L}{G} \frac{u_G \rho_L D}{\mu} F(K_{pt} f) \right] \quad (4)$$

where u_G is the velocity of the gas, ρ_L is the density of the liquid, D is the diameter of the collecting drops, μ is the viscosity of the gas, and $F(K_{pt}f)$ is given by:

$$F(K_{pt}f) = [0.7 K_{pt}f + 1.4 \ln \left(\frac{K_{pt}f + 0.7}{0.7} \right) + \frac{0.49}{0.7 + K_{pt}f}] \frac{1}{K_{pt}} \quad (5)$$

where f is an empirical parameter (usually $f = 0.5$), and K_{pt} is the inertial impaction parameter calculated at conditions in the throat:

$$K_{pt} = \frac{u_G \rho_p C' d^2}{9\mu D} \quad (6)$$

where u_G is the gas velocity in the throat, ρ_p is the particle density, C' is the Cunningham correction factor, and d is the diameter of the particles.

The diameter of the drops can be calculated from an empirical correlation by Nukiyama and Tanasawa.¹

$$D \text{ (cm)} = \frac{50}{u_G \text{ (cm/sec)}} + 91.8 \left(\frac{L}{G} \right)^{1.5} \quad (7)$$

The assumptions used to derive all these equations are given by Calvert et al.¹ and the interested reader is referred there for additional information.

It should be noted that equation (4) is valid only when inertial impaction is the dominant particle collection mechanism. Inertial impaction is the dominant mechanism for particles with diameters greater

than about 0.1 microns. Thus equation (4) is valid in most situations of practical interest.

The parameter "f" in equation (5) is an empirical parameter which includes all unmodelled effects. Experimental data for industrial scale scrubbers indicate that f is essentially a constant with a value of 0.5.

SR-52 PROGRAM

The SR-52 program is a two card program which provides a numerical solution to equation (3) for a log-normal particle size distribution. Card 1 is used to enter the data, calculate pressure drop, and calculate constants used in calculations performed using Card 2. Card 2 uses a trapezoidal rule numerical integration to solve equation (3) over the limits d_{initial} to d_{final} .

Card 1

The program on Card 1 is used to carry out three activities:

1. Enter and store data on scrubber parameters, gas conditions, and particle size distribution.
2. Calculate constants used in the program contained on Card 2.
3. Calculate pressure drop across the scrubber.

Each of these activities is discussed below.

The data on scrubber parameters, gas conditions, and particle size distribution are entered in a specific order.

- T - Gas temperature ($^{\circ}\text{C}$) stored in R_{03}
- f - Empirical parameter (usually 0.5) stored in R_{04}
- d_g - Mass mean particle diameter (microns) stored in R_{08}
- σ_g - Geometric standard deviation stored in R_{10}
- d_i - Initial particle diameter for integration (micron)
stored in R_{11}
- d_f - Final particle diameter for integration (micron)
stored in R_{12}
- Δd - Particle diameter increment for integration (micron)
stored in R_{13}
- ρ_L - Density of liquid (gm/cm^3) stored in R_{14}
- L/G - Liquid to gas flow rate ratio (m^3/m^3) stored in R_{15}
- u_G - Gas velocity in venturi throat (cm/sec) stored in R_{16}
- μ - gas viscosity (poise) stored in R_{17}
- ρ_p - Density of the particles (gm/cm^3) stored in R_{18}

Data entry is accomplished by entering gas temperature then pushing A. All other data are entered using RUN key. Each one of the entered data is printed as it is entered.

As soon as the last entry ρ_p is made, the constants for Card 2 are calculated, drop diameter is calculated and printed in cm, and pressure drop is calculated and printed in cm water.

Calculation of Constants for Card 2

As soon as ρ_p is entered the program automatically calculates and stores the following constants for use in the program on Card 2:

$$\frac{u_G p}{9 \mu D}$$
$$- 2 \ln^2 \sigma_g$$
$$\sqrt{2\pi} \ln \sigma_g$$
$$\frac{2}{55} \frac{L}{G} \frac{u_G \rho_L D}{\mu}$$

In order to calculate these constants, the program twice calculates and prints drop diameter, D , in cm.

The calculation routine to calculate constants can be called from the keyboard by pressing C. The calculator will then calculate all the constants, and calculate and print drop diameter and pressure drop. This procedure is especially useful (as is discussed in the section on the use of the program) when it is necessary to perform several calculations where only a few variables, such as gas velocity, are changed from run to run.

NOTE: This procedure cannot be used in cases where the log-normal size distribution parameters are changed.

Calculation of Pressure Drop

After the calculation of constants is complete, the calculator

automatically calculates and prints the pressure drop across the venturi in cm of water. The pressure drop calculation routine can be called from the keyboard by pressing 2nd A'. The effects of various combinations of gas velocity and liquid/gas flow rate ratio on pressure drop can be investigated by storing u_G in R_{16} and L/G in R_{15} , then pressing 2nd A'.

Card 2

Card 2 is used to calculate the overall penetration for a log-normal particle size distribution. The method of solution is discussed below.

Equation (1) can be approximated by:

$$Pt_0 = \int_0^{\infty} Pt(d)f(d)dd \approx \int_{d_i}^{d_f} Pt(d)f(d)dd \quad (8)$$

where d_i is the initial particle diameter and d_f is the final particle diameter.

The solution to equation (8), for the case where the particle size distribution is log-normal, is accomplished by the program carried on Card 2. Equation (8) is solved using a trapezoidal rule numerical integration:

$$Pt_0 = \Delta d \left[\frac{Pt(d_i)f(d_i)}{2} + Pt(d_i + \Delta d)f(d_i + \Delta d) + Pt(d_i + 2\Delta d)f(d_i + 2\Delta d) \right. \\ \left. + \dots \frac{Pt(d_f)f(d_f)}{2} \right] \quad (9)$$

where $Pt(d)$ is given by:

$$Pt(d) = \exp \left\{ K_1 \left[-0.7 - K_2 C' d^2 f + 1.4 \ln \left(\frac{K_2 C' d^2 f + 0.7}{0.7} \right) + \frac{0.49}{0.7 \pm K_2 C' d^2 f} \right] \frac{1}{K_2 C' d^2} \right\} \quad (10)$$

where $K_1 = \frac{2}{55} \frac{L}{G} \frac{u_{GpL}}{\mu} D$ and $K_2 = \frac{u_{Gp}}{\mu}$

both are calculated using Card 1,

C' is the Cunningham correction factor and is calculated in the program by:

$$C' = 1 + \frac{2T(^{\circ}K)}{D(\mu m) \times 10^8} [2.79 + 0.894 \exp \left(\frac{2.47 \times 10^7 d(m)}{T(^{\circ}K)} \right)] \quad (11)$$

$Pt(d)$ is calculated in subroutine E.

For a log-normal size distribution, $f(d)$ is given by:

$$f(d) = \frac{1}{2\pi \ln \sigma_g^2 d} \exp \left[\frac{-\ln^2 (d/d_g)}{2 \ln^2 \sigma_g} \right] \quad (12)$$

where d_g is the geometric mass mean particle diameter (μm) and σ_g is the geometric standard deviation.

$f(d)$ is calculated in subroutine D.

At the completion of the numerical solution, the calculator will print Pt_0 , d_i and d_f . Pt_0 is stored in R_{98} .

Because particle size distributions span several orders of magnitude of particle diameter, it is useful to break equation (8) into increments,

each with its own Δd , and sum the solutions to the increments to obtain the overall solution; i.e.,

$$P_{t_0} = \int_{d_i}^{d_f} P_t(d)f(d)dd = \int_{d_i}^{d_1} P_t(d)f(d)dd + \int_{d_1}^{d_2} P_t(d)f(d)dd + \dots + \int_{d_n}^{d_f} P_t(d)f(d)dd \quad (13)$$

The summation is automatically carried out in R_{98} . In order to use R_{98} for the summation the user must store 0 in R_{98} when beginning a problem.

The user must determine his own total integration limits, how many increments to divide the total integral into, and the Δd for each increment.

In general overall integration from 0.1 to 20 microns with increments of

0.1 to 1.0 microns ($\Delta d = 0.1$)

1.0 to 10 microns ($\Delta d = 0.5$)

10 to 20 microns ($\Delta d = 2$)

is more than adequate. For particle size distributions with small d_g and large σ_g , the lower limit should be reduced. For cases where the pressure drop exceeds, say, 40 cm of water, integration past 5 μm is generally not necessary. When the mass mean particle diameter is small, say, less than 2 μm , Δd should not exceed 0.2 until integration is past d_g .

Use of the SR-52 Program

The SR-52 program provides a quick way to determine venturi scrubber performance. Three possible uses are:

1. Determine pressure drop and penetration through a given scrubber on a given aerosol. (See Example 1.)
2. Determine pressure drop required to meet a given outlet emission. (See Example 2.)
3. Determine effects of changes in particle size distribution on penetration through a given scrubber. (See Example 3.)

The SR-52 program as written will print all input data, drop diameter, pressure drop, overall penetration, and integration limits using the PC-100A printer.

The printer output is arranged as follows:

$T, ^\circ\text{C}$

f

$d_g, \mu\text{m}$

σ_g

$d_i, \mu\text{m}$

d_f , μm
 Δd , μm
 ρ_L , gm/cm^3
 L/G , m^3/m^3 or cm^3/cm^3
 u_G , cm/sec
 μ , poise
 ρ_p , gm/cc
 D , μm
 D , μm
 Space
 Δp , cm water
 Space
 Pt_0
 d_i , μm
 d_f , μm

All the above are automatically printed.

Pt_0 for all increments is manually printed by pressing RCL 98 2nd prt and follows d_f .

The program can be used without the printer as follows:

1. Card 1

Pressure drop is displayed at end of calculation.

Drop diameter can be displayed by pressing D.

2. Card 2

Penetration due to particles between d_1 and d_2 can be displayed by the following steps:

Press RCL 19

Press X

Press RCL 13

Press =

Penetration will then be displayed.

Overall penetration can be displayed by pressing RCL 98, the same step as required when using the printer.

Example 1

Calculate overall penetration and pressure drop of a scrubber operating under given conditions.

Given:

Temperature	= 65°C
Particle size distribution--	
mass mean diameter,	= 1.5 μm
geometric standard deviation	= 2.0
Liquid/gas ratio	= $9 \times 10^{-4} \text{ cm}^3/\text{cm}^3$
Gas velocity	= $100 \times 10^2 \text{ cm/sec}$
Gas viscosity	= $1.8 \times 10^{-4} \text{ poise}$
Liquid viscosity	= 1.0 gm/cm^3
Particle density	= 2.0 gm/cm^3
Empirical factor	= 0.5

Solution:

Divide integration into two increments:

$$P_{t_0} \sim \int_{0.1}^{1.5} P_t(d)f(d)dd + \int_{1.5}^5 P_t(d)f(d)dd$$

Enter Card 1, sides A and B:

<u>Step</u>	<u>Procedure</u>	<u>Enter</u>	<u>Press</u>	<u>Display</u>	<u>Print</u>
1	Enter Card 10		<u>STO 98</u>	0	
2	Enter data	T (65)	<u>A</u>	3.38-02	65.
		f (.5)	<u>RUN</u>	5.01	5.01
		d _g	<u>RUN</u>	1.01	1.5 00
		σ _g (2)	<u>RUN</u>	7.00	2.
		d _i (.1)	<u>RUN</u>	6.00	0.1
		d _f (1.5)	<u>RUN</u>	5.00	1.5
		Δd (.1)	<u>RUN</u>	4.00	0.1
		ρ _L (1)	<u>RUN</u>	3.00	1.
		L/G (9EE ± 4)	<u>RUN</u>	2.00	9.-04
		u _G (100EE2)	<u>RUN</u>	1.00	1. 04
		μ (1.8EE ± 4)	<u>RUN</u>	0.00	1.8-04
		p _p (2)	<u>RUN</u>		2. 00
					7.4786-03
					7.4786-03
				7.41601	7.416 01

<u>Step</u>	<u>Procedure</u>	<u>Enter</u>	<u>Press</u>	<u>Display</u>	<u>Print</u>
3	Enter Card 2				
4	Calculate Pt_0 $0.1 < d < 1.5 \mu m$		<u>A</u>	1.5	1.614021483-02
					1. -01
	(1.614×10^{-2} is the penetration of particles with $0.1 < d < 1.5 \mu m$)				1.5 00
5	Carry integration past $1.5 \mu m$				
6	Clear R_{19}	0	<u>STO 19</u>	0	
7	Store new d_i	1.5	<u>STO 11</u>	1.5	
8	Store new d_f	5.0	<u>STO 12</u>	5.	
9	Store new Δd	0.5	<u>STO 13</u>	0.5	
10	Calculate Pt_0 $1.5 < d < 5.0 \mu m$		<u>A</u>		.0012172657
					1.5
					5.
11	Recover and print		<u>RCL 98</u>	.0173574805	
	Pt_0 $0.1 < d < 5.0 \mu m$		<u>2nd Prt</u>		.0173574805

Figure 1, the Example 1 printer output, shows all printer output from both Cards 1 and 2.

In summary:

$\Delta p = 74$ cm water,

$Pt_0 = 0.017$, and

Efficiency, $E_0 = 1 - Pt_0 = 0.983$.

65.	PRT
5. -01	PRT
1.5 00	PRT
2.	PRT
0.1	PRT
1.5	PRT
0.1	PRT
1.	PRT
9. -04	PRT
1. 04	PRT
1.8-04	PRT
2. 00	PRT
7.4786-03	PRT
7.4786-03	PRT
7.416 01	PRT
1.614021483-02	PRT
1. -01	PRT
1.5 00	PRT
.0012172657	PRT
1.5	PRT
5.	PRT
.0173574805	PRT

Figure 1. PC-100A printer output for example 1--overall penetration and scrubber pressure drop.

Example 2

This example shows how to use the program to estimate pressure drop required for a given outlet emission.

Given:

Allowable emissions	=	0.01 mg/dNm^{3*}
Inlet loading	=	1 mg/dNm^3
Gas temperature	=	65°C
Particle size distribution--		
mass mean diameter	=	$3 \text{ }\mu\text{m}$
geometric standard deviation	=	2
Particle density	=	2 gm/cm^3

Solution:

Required penetration = 0.01.

(Required efficiency = $1 - 0.01 = 0.99$.)

Assume $f = 0.5$.

For first guess let $L/G = 9 \times 10^4 \text{ m}^3/\text{m}^3$, and

$$u_G = 1.2 \times 10^4 \text{ cm/sec.}$$

Integrate over two intervals:

0.1 to 1 with $\Delta d = 0.1$, and

1 to 5 with $\Delta d = 0.2$.

* dNm^3 is dry normal cubic meters; normal conditions are 1 atm and 20°C

<u>Step</u>	<u>Procedure</u>	<u>Enter</u>	<u>Press</u>	<u>Display</u>	<u>Print</u>
1	Enter Card 1				
2	Enter data	T(65)	<u>A</u>	3.38-02	65.
		f (.5)	<u>RUN</u>	5. -01	5. -01
		d _g (3)	<u>RUN</u>	1.01	3. 00
		σ _g (2)	<u>RUN</u>	7.00	2. 00
		d _i (.1)	<u>RUN</u>	6.00	1. -01
		d _f (1)	<u>RUN</u>	5.00	1. 00
		Δd (.1)	<u>RUN</u>	4.00	1. -01
		ρ _L (1)	<u>RUN</u>	3.00	1. 00
		L/G(9EE ± 4)	<u>RUN</u>	2.00	9. -04
		u _G (1.2EE4)	<u>RUN</u>	1.00	1.2 04
		μ (1.8EE ± 4)	<u>RUN</u>	0.00	1.8 -04
					2. 00
		p (2)	<u>RUN</u>		6.645266667-03
					6.645266667-03
				1.06790402	Space
					1.067904 02
					Space
3	Clear R ₉₈	0	<u>STO 98</u>	0	
4	Enter Card 2				
5	Calculate Pt ₀ 0.1 < d < 1 μm		<u>A</u>	1.	8.787862447-04
					1. -01
					1. 00
6	Carry integration past 1.0 m				
7	Clear R ₁₉	0	<u>STO 19</u>	0	
8	Store new d _i	1.	<u>STO 11</u>	1.	

<u>Step</u>	<u>Procedure</u>	<u>Enter</u>	<u>Press</u>	<u>Display</u>	<u>Print</u>
9	Store new d_f	5.	<u>STO 12</u>	5.	
10	Store new Δd	0.2	<u>STO 13</u>	0.2	
11	Calculate Pt_0 $1.0 < d < 5.0 \mu m$	<u>A</u>		5.	.0010940953 1. 5.
12	Recover and print		<u>RCL 98</u>	.0019728815	
	Pt_0 $0.1 < d < 5.0 \mu m$		<u>2nd prt</u>		.0019728815
13	Because Pt_0 is too low, reduce Δp by decreasing u_G				
14	Enter Card 1				
15	Store new u_G 6×10^3		<u>STO 16</u>	6.03	
16	Store d_i	0.1	<u>STO 11</u>	01. -01	
17	Store d_f	1.	<u>STO 12</u>	1. 00	
18	Store Δd	0.1	<u>STO 13</u>	1. -01	
19	Clear R_{98}	0	<u>STO 98</u>	0.	
20	Calculate new constants and Δp	<u>2nd stflg 2 C</u>		2.66976 01 (Drop diameter) (New Δp)	1.081193333-02 1.081193333-02 Space 2.66976 01 Space
21	Enter Card 2				
22	Calculate Pt_0 $0.1 < d < 1.0 \mu m$		<u>A</u>	1.	.0081657664 0.1 1.
23	Carry integration past $1.0 \mu m$				
24	Clear R_{19}	0	<u>STO 19</u>	0.	
25	Store new d_i	1.	<u>STO 11</u>	1.	
26	Store new d_f	5.	<u>STO 12</u>	5.	

<u>Step</u>	<u>Procedure</u>	<u>Enter</u>	<u>Press</u>	<u>Display</u>	<u>Print</u>
27	Store new Δd	0.1	<u>STO 13</u>	0.1	
28	Calculate Pt_0 $1.0 < d < 5.0 \mu m$		<u>A</u>	5.	0.008565109 1. 5.
29	Recover and print Pt_0 $0.1 < d < 5.0 \mu m$		<u>RCL 98</u> <u>2nd prt</u>	.0167308754	.0167308754
30	Because this Pt_0 is too high increase Δp by increasing u_G to 7.2×10^3 cm/sec.				
31	Enter Card 1				
32	Store new u_G 7.2×10^3		<u>STO 16</u>	7.2 EE3	
33	Store new d_i	0.1	<u>STO 11</u>	1. -01	
34	Store new d_f	1.0	<u>STO 12</u>	1. 00	
35	Store new Δd	0.1	<u>STO 13</u>	1. -01	
36	Clear R_{98}	0.	<u>STO 98</u>	0.	
37	Calculate new constants and Δp		<u>2nd stflg 2</u> <u>C</u>	3.844454401 (new D) (new Δp)	9.423044444-03 9.423044444-03 3.8444544 01
38	Enter Card 2				
39	Calculate Pt_0 $0.1 < d < 1.0 \mu m$		<u>A</u>	1.0	.0049534354 0.1 1.
40	Carry integration past $1.0 \mu m$				
41	Clear R_{19}	0	<u>STO 19</u>	0	
42	Store new d_i	1.	<u>STO 11</u>	1.	
43	Store new d_f	5.	<u>STO 12</u>	5.	
44	Store new d	0.2	<u>STO 13</u>	0.2	

<u>Step</u>	<u>Procedure</u>	<u>Enter</u>	<u>Press</u>	<u>Display</u>	<u>Print</u>
45	Calculate Pt_0 $1.0 < d < 5.0 \text{ } \mu\text{m}$		<u>A</u>	5.0	.0051689409 1. 5.
46	Recover and print $Pt_0 \text{ } 0.1 < d < 5 \text{ } \mu\text{m}$		<u>RCL 98</u>	.0101223763	
			<u>2nd prt</u>		.0101223763

This is close enough to desired penetration.

In summary:

$$\Delta p = 38.4 \text{ cm water,}$$

$$Pt_0 = 0.010, \text{ and}$$

$$E_0 = 0.9909.$$

PC-100A printer output for Example 2 is shown in Figure 2.

Example 3

Determine the effects of changing size distribution parameters:

from $d_g = 3, \sigma_g = 2$
to $d_g = 3, \sigma_g = 3$

on overall penetration for a scrubber operating under given conditions.

Given:

Temperature = 65°C
Gas velocity = $1 \times 10^4 \text{ cm/sec}$
Particle density = 2 gm/cm^3

65.	PRT
5. -01	PRT
3. 00	PRT
2. 00	PRT
1. -01	PRT
1. 00	PRT
1. -01	PRT
1. 00	PRT
9. -04	PRT
1.2 04	PRT
1.8-04	PRT
2. 00	PRT
6.645266667-03	PRT
6.645266667-03	PRT
1.067904 02	PRT
8.787862447-04	PRT
1. -01	PRT
1. 00	PRT
.0010940953	PRT
1.	PRT
5.	PRT
.0019728815	PRT
1.081193333-02	PRT
1.081193333-02	PRT
2.66976 01	PRT
.0081657664	PRT
0.1	PRT
1.	PRT
0.008565109	PRT
1.	PRT
5.	PRT
.0167308754	PRT
9.423044444-03	PRT
9.423044444-03	PRT
3.8444544 01	PRT
.0049534354	PRT
0.1	PRT
1.	PRT
.0051689409	PRT
1.	PRT
5.	PRT
.0101223763	PRT

Figure 2. PC-100A printer output for example 2--scrubber pressure drop vs. outlet emission.

Liquid density = 1 gm/cm³
 Gas viscosity = 1.8 x 10⁻⁴ poise
 Liquid/gas ratio = 1 x 10⁻³ m³/m³

Solution:

Integrate over two intervals:

$d_i = 0.1$ $d_f = 1.0$ $\Delta d = 0.1$
 $d_i = 1.0$ $d_f = 5.0$ $\Delta d = 0.2$

Step	Procedure	Enter	Press	Display	Print
1	Enter Card 1				
2	Enter data	T(65)	<u>A</u>	3.38-02	65
		f(.5)	<u>RUN</u>	5. -01	5. -01
		d _g	<u>RUN</u>	1.01	3. 00
		σ _g	<u>RUN</u>	7.00	2. 00
		d _i (.1)	<u>RUN</u>	6.00	1. -01
		d _f (1.)	<u>RUN</u>	5.00	1. 00
		Δd(.1)	<u>RUN</u>	4.00	1. -01
		ρ _L (1)	<u>RUN</u>	3.00	1. 00
		L/G(1EE ±3)	<u>RUN</u>	2.00	1. -03
		u _G (1EE4)	<u>RUN</u>	1.00	1. 04
		μ (1.8EE ± 4)	<u>RUN</u>	0.00	1.8-04
		ρ _p (2)	<u>RUN</u>		2. 00
					7.902970892-03
					7.902970892-03
3	Clear R ₉₈	0	<u>STO 98</u>	8.24 01	8.24 01

Step	Procedure	Enter	Press	Display	Print
4	Enter Card 2				
5	Calculate Pt_0 $0.1 < d < 1.0 \mu m$	<u>A</u>		1.0	1.144198314-03 1. -01 1. 00
6	Carry integration past $1.0 \mu m$				
7	Clear R_{19}	0	<u>STO 19</u>	0	
8	Store new d_i	1.	<u>STO 11</u>	1.	
9	Store new d_f	5.	<u>STO 12</u>	5.	
10	Store new Δd	0.2	<u>STO 13</u>	0.2	
11	Calculator Pt_0 $1.0 < d < 5.0 \mu m$	<u>A</u>		5.0	7.669028639-04 1. 0 5. 0
12	Recover and print				
	Pt_0 $0.1 < d < 5.0 \mu m$		<u>RCL 98</u>	1.911101177-03	
			<u>2nd prt</u>		1.911101177-03
	The above is overall penetration for $d_g = 3$ and $\sigma_g = 2$.				
13	Determine penetration for $d_g = 3$ and $\sigma_g = 3$				
14	Enter Card 1				
15	Clear flag 2		<u>INV 2nd stflg 2</u>		
16	Clear R_{98}	0	<u>STO 98</u>	0	
17	Store d_g	3	<u>STO 08</u>	3	
18	Store σ_g	3	<u>STO 10</u>	3	
19	Store d_i	.1	<u>STO 11</u>	.1	
20	Store d_f	1	<u>STO 12</u>	1.	
21	Calculate constants		<u>C</u>		.0079029709
	and Δp				7.902970892-03 space 8.2401 8.24 01

<u>Step</u>	<u>Procedure</u>	<u>Enter</u>	<u>Press</u>	<u>Display</u>	<u>Print</u>
22	Enter Card 2				
23	Calculate Pt_0 $0.1 < d < 1 \mu m$		<u>A</u>	1.	.0116402843
					0.1
					1.
24	Carry integration past $1.0 \mu m$				
25	Clear R_{19}	0	<u>STO 19</u>	0.	
26	Store new d_i	1.	<u>STO 11</u>	1.	
27	Store new d_f	5.	<u>STO 12</u>	5.	
28	Store new Δd	0.2	<u>STO 13</u>	0.2	
29	Calculate Pt_0 $1.0 < d < 5.0 \mu m$		<u>A</u>	5.	.0006463882
					1.
					5.
30	Recover and print				
	Pt_0 $0.1 < d < 5.0 \mu m$		<u>RCL 98</u>	.0122866724	
			<u>2nd prt</u>		.0122866724

Note the large increase in penetration due to the increase in geometric standard deviation.

Printer output for Example 3 is shown in Figure 3.

COMPARISON WITH EXPERIMENTAL DATA

The SR-52 program predicts overall penetrations and pressure drops which are in good agreement with experimental data. Comparisons between calculated and measured penetrations and efficiencies are given in Table 1.

65.	PRT
5. -01	PRT
3. 00	PRT
2. 00	PRT
1. -01	PRT
1. 00	PRT
1. -01	PRT
1. 00	PRT
1. -03	PRT
1. 04	PRT
1.8-04	PRT
2. 00	PRT
7.902970892-03	PRT
7.902970892-03	PRT
8.24 01	PRT
1.144198314-03	PRT
1. -01	PRT
1. 00	PRT
7.669028639-04	PRT
1. 00	PRT
5. 00	PRT
1.911101177-03	PRT
.0079029709	PRT
7.902970892-03	PRT
8.24 01	PRT
.0116402843	PRT
0.1	PRT
1.	PRT
.0006463882	PRT
1.	PRT
5.	PRT
.0122866724	PRT

Figure 3. PC-100A printer output for example 3--changing scrubber size distribution parameters.

Table 1. COMPARISON BETWEEN SR-52 SCRUBBER PROGRAM PREDICTED
RESULTS AND EXPERIMENTAL DATA

Plant	Measured		Calculated	
	Δp , cm water	Pt_o	Δp , cm water	Pt_o
1	45.7	0.015	46	0.016
2	25	0.025	25	0.028
3	100	0.005	105	0.004

ELECTROSTATIC PRECIPITATOR

MATHEMATICAL MODEL

The SR-52 program is based on the Environmental Protection Agency/Southern Research Institute (EPA/SoRI) mathematical model of electrostatic precipitation described by Gooch et al.² Only a brief discussion of the model will be given here.

The theoretical overall penetration (1 minus efficiency) through an electrostatic precipitator (ESP) is given by:

$$Pt_0 = \int_0^{\infty} Pt(d)f(d)dd \quad (14)$$

where $Pt(d)$ is the penetration of particles with diameter d , and $f(d)$ is the fraction of the particles with diameters between d and $d + dd$.

The EPA/SoRI model is based on the Deutch-Andersen equation for particle penetration through an ESP:

$$Pt(d) = \exp [-w(d)A/V] \quad (15)$$

where $Pt(d)$ is the theoretical penetration of particles with diameter d , $w(d)$ is the electrical migration velocity of particles with diameter d , A is the collector plate area, and V is the volumetric flow rate of gas.

For the situation where the particle charge, q , and the electric field at the plate, E_p , are known, $w(d)$ can be calculated from:

$$w(d) = (q E_p C') / (3\pi d \mu) \quad (16)$$

where C' is the Cunningham correction factor and μ is the gas viscosity.

The calculations necessary to determine q and E_p are beyond the capabilities of the SR-52. These calculations were carried out in the EPA/SoRI model for a typical ESP collecting fly ash, and the results are incorporated into the SR-52 program.

The penetration predicted by equation (15) is generally less than the penetration measured in industrial ESP because certain non-ideal factors (e.g., non-uniform gas flow, sneakage, and reentrainment) act to increase penetration. Methods for estimating the effects of non-uniform gas flow, sneakage, and reentrainment are described by Gooch et al.² whose method is used in the SR-52 program.

Gooch et al. have shown that the effects of these non-ideal factors can be estimated by:

$$Pt'(d) = \exp \left[\frac{-w(d)A}{BF V} \right] \quad (17)$$

where $Pt'(d)$ is the corrected penetration, B is the correction factor for sneakage and reentrainment, and F is the correction factor for non-uniform gas flow.

$$B = \frac{\ln Pt(d)}{N_s \ln [S + (1-S)Pt(d)^{1/N_s}]} \quad (18)$$

where N_s = number of baffled sections, and S is the fraction of particles that are reentrained and that bypass the electrified region per section.

$$F = 1.0 + 0.766 [1-Pt(d)]^\sigma + 0.0755 \sigma \ln [1/Pt(d)] \quad (19)$$

where σ is the normalized standard deviation of the gas flow ($\sigma = 0.25$ is generally considered good).

Note that both B and F are particle size dependent.

The overall penetration is given by:

$$Pt_0 = \int_0^\infty Pt'(d)f(d)dd \quad (20)$$

It is this equation that is solved by the SR-52 program.

SR-52 PROGRAM

The SR-52 program solves equation (20) over the finite limits of d_i to d_f using a trapezoidal rule numerical integration.

$Pt(d)$ is calculated based on second order polynomial curve fits to $W(d)$ vs d curves given by Gooch et al.² These curves are based on typical electrical conditions for an ESP collecting fly ash.

Curves for the following cases were used to develop the least squares curve fit parameters shown in Table 2:

- Cold-side ESP current density 5 na/cm²
- Cold-side ESP current density 20 na/cm²
- Cold-side ESP current density 40 na/cm²
- Hot-side ESP current density 30 na/cm²

Gas temperatures are 150°C and 370°C for cold- and hot-side ESP's, respectively.

The current density that should be used in the calculations depends on the dust resistivity. The relationship between allowable current density (cold-side ESP) and dust resistivity is based on empirical data reported by Hall.⁵ Hall's relationship can be written:

$$j = \frac{6.31 \times 10^{11}}{\rho^{0.987}}$$

where j is current density (in na/cm²) and ρ is the dust resistivity (in ohm-cm).

When the current density predicted by the equation above is less than 5 na/cm², a hot-side ESP should be considered and the hot-side parameters should be used.

This is a two card program: Card 1 is used to enter and store data and to calculate constants; Card 2 is used to perform the numerical integration.

Table 2. MIGRATION VELOCITY VS. PARTICLE DIAMETER CURVE FIT PARAMETERS
FOR VARIOUS ESP CURRENT DENSITIES

Current Density na/cm ²	Temperature °C	Particle Diameter Limits μm	Curve Fit Parameters for Migration Velocity ^a		
			First, a	Second, b	Third, c
5	150	d < 2	1.15987	0.3	0.21188
5	150	d > 2	0.94818	0.811698	-0.0003504
20	150	d < 2	2.85176	1.06416	0.48567
20	150	d > 2	2.2525	2.3348	0.002652
40	150	d < 2	4.2029	1.5294	0.6956
40	150	d > 2	2.8475	3.6296	0.01137
30	370	d < 2	3.9943	-1.2175	1.02250
30	370	d > 2	2.5917	1.5032	0.005790

^aParameters for $w(d) = a + bd + cd^2$ cm/sec

Card 1

The program on Card 1 is used to:

1. Enter and store data on ESP parameters, gas conditions, and particle size distribution.
2. Calculate constants used in Card 2.

The following data are entered and stored by pressing the indicated buttons:

Enter Data

Press

Mass mean particle diameter, d_g (μm)

A

Geometric standard deviation, σ_g

RUN

First curve fit parameter for migration velocity, a

B

Second " " " " " " , b

RUN

Third " " " " " " , c

RUN

Specific collector area, A/V ($\text{cm}^2/\text{Acm}^3/\text{sec}$), or

C

Specific collector area, A/V ($\text{ft}^2/1000 \text{ ACFM}$)

stflg 1 C

Normalized standard deviation of gas velocity distribution

D

Number of baffled sections, N_s

E

Sneakage-reentrainment fraction, S

RUN

Initial particle diameter, d_i (μm)

2nd A'

Final particle diameter, d_f (μm)

RUN

Particle diameter increment, Δd (μm)

RUN

Each of the input data is printed as it is entered.

Card 2

Card 2 is used to perform the numerical integration of equation (20) for a log-normal size distribution over the finite limits d_i to d_f using the trapezoidal rule numerical integration technique:

$$Pt_0 = \int_{d_i}^{d_f} Pt'(d)f(d)dd = \Delta d \left\{ \frac{Pt'(d_i)}{2} + Pt'(d_i + \Delta d) + Pt'(d_i + 2\Delta d) + \dots + \frac{Pt'(d_f)}{2} \right\} \quad (21)$$

where $Pt'(d)$ is given by equation (17) and $w(d)$ is given by:

$$w(d) = a + bd + cd^2. \quad (22)$$

Data a, b, and c are input using Card 1.

$Pt'(d)$ is calculated in routine E.

For a log-normal size distribution, $f(d)$ is given by:

$$f(d) = \frac{1}{\sqrt{2\pi} \ln \sigma} \exp \left[\frac{-\ln^2 (d/d_g)}{2 \ln^2 \sigma_g} \right] \quad (23)$$

where d_g is the mass mean particle diameter, μm , and σ_g is the geometric standard deviation.

Fraction of particles with diameter d, $f(d)$, is calculated in subroutine D.

At the completion of the numerical solution, the calculator will print Pt_0 , d_i , and d_f . Pt_0 is stored in R_{98} .

Because particle size distributions span several orders of magnitude of particle diameter, it is useful to break equation (8) into increments (each with its own Δd) and sum the solutions to the increments to obtain the overall solution; i.e.,

$$Pt_0 = \int_{d_i}^{d_f} Pt(d)f(d)dd = \int_{d_k}^{d_1} Pt(d)f(d)dd + \int_{d_i}^{d_2} Pt(d)f(d)dd \quad (24)$$

$$+ \dots + \int_{d_n}^{d_f} Pt(d)f(d)dd$$

The summation is automatically carried out in R_{98} . The results of the summation must be manually recalled and printed by pressing RCL 98 2nd prt.

The user must determine: his own total integration limits, the number of increments into which to divide the total integral, and the Δd for each integral.

In general, overall integration from 0.1 to 20 microns with increments of

0.1 to 1.0 microns ($\Delta d = 0.1$)

1.0 to 10 microns ($\Delta d = 0.5$)

10 to 20 microns ($\Delta d = 2$)

is more than adequate.

Use of the SR-52 Program

The SR-52 program provides a quick way to estimate ESP performance.

Five possible uses of the program are to:

1. Determine penetration of a given aerosol through a given outlet emission standard for a given aerosol. (See Example 4.)
2. Determine specific collector area required to meet a given outlet emission standard for a given aerosol. (See Example 5.)
3. Determine effects of changes in particle size distribution on penetration through a given ESP. (See Example 6.)
4. Determine effects of changes in dust resistivity on penetration through a given ESP. (See Example 7.)
5. Determine effects of changes in non-ideal factors on penetration through a given ESP. (See Example 8.)

The SR-52 program as written will print all input data and penetration through a given increment using the PC-100A printer. The overall penetration summed over all increments must be recovered and printed manually by pressing RCL 98 2nd prt.

The printer output is arranged as follows:

```

dg, μm
σg
a } parameters for w(d) = a + bd + cd2
b }
c }
A/V, cm2/Acm3/sec or ft2/103KACFM
σ
Ns
S
di
df
Δd
space
A/V, cm2/Acm3/sec
space
Pt0

```

The program can be used without the printer with no changes. Pt₀ for each increment will be displayed at end of calculation. Pt₀ summed over all increments can be displayed by pressing RCL 98.

Steps to follow in using program:

1. Determine dust resistivity, ρ, in ohm-cm.
2. Determine allowable current density, j, in na/cm² from Hall's⁵ empirical correlation:

$$j = \frac{6.31 \times 10^{11}}{\rho^{0.987}}$$

3. Determine least squares parameters for $w(d) = a + bd + cd^2$ from Table 2 using current density nearest to but not exceeding that calculated in Step 2.
4. Determine A/V .
5. Enter data using Card 1.
6. Determine Pt_0 using Card 2.

Example 4

Calculate overall penetration through an ESP for given conditions.

Given:

Cold-side ESP A/V	= $0.7 \text{ cm}^2/\text{Acm}^3/\text{sec}$ ($356 \text{ ft}^2/10^3 \text{ ACFM}$)
Dust resistivity	= $4 \times 10^{10} \text{ ohm-cm}$
Mass mean particle diameter	= $15 \text{ }\mu\text{m}$
Geometric standard deviation	= 4
Normalized standard deviation of gas velocity distribution	= 0.25
Number of baffled sections	= 4
Fractional sneakage/reentrainment	= 0.1
Cold-side ESP T	= 150°C

Solution:

$$Pt_0 = \int_0^{\infty} Pt'(d)f(d)dd$$

Divide integration into two increments:

0.1 to 2 μm with $\Delta d = 0.1$, and

2.0 to 20 μm with $\Delta d = 1$.

Calculate allowable current density:

$$j = \frac{6.31 \times 10^{11}}{(4 \times 10^{10})^{0.987}} = 22 \text{ na/cm}^2$$

Use a, b, c for 20 na/cm^2 .

<u>Step</u>	<u>Procedure</u>	<u>Enter</u>	<u>Press</u>	<u>Display</u>	<u>Print</u>
1	Enter Card 1				
2	Enter all data	$d_g(15)$	A	15	15.
		$\sigma_g(4)$	<u>RUN</u>	3.474924643	4.
		a(2.85176)	<u>B</u>	2.85176	2.85176
		b(1.06416)	<u>RUN</u>	1.06416	1.06416
		c(0.48567)	<u>RUN</u>	0.48567	0.48567
		A/V (0.7)	<u>C</u>	-0.7	0.7
		$\sigma(0.25)$	<u>D</u>	0.018875	0.25
		$N_s(4)$	<u>E</u>	4.	4.
		S(0.1)	<u>RUN</u>	0.1	0.1
		$d_i(0.1)$	<u>2nd A'</u>	0.1	0.1
		$d_f(2.0)$	<u>RUN</u>	2.0	2.
		$\Delta d(0.1)$	<u>RUN</u>	0.7	0.1
					space
					0.7

<u>Step</u>	<u>Procedure</u>	<u>Enter</u>	<u>Press</u>	<u>Display</u>	<u>Print</u>
3	Enter Card 2				
4	Calculate Pt_0 $0.1 < d < 2.0 \mu m$ (calculation takes about 5 minutes)		<u>A</u>	2.	.0060170031 2.
5	Carry integration past $2.0 \mu m$				
6	Clear R_{19}	0.	<u>STO 19</u>	0.	
7	Store new d_i	2.	<u>STO 16</u>	2.	
8	Store new d_f	20.	<u>STO 17</u>	20.	
9	Store new Δd	1.	<u>STO 18</u>	1.	
10	Store new a, b, c for $d > 2.0 \mu m$				
		2.2525	<u>STO 05</u>	2.2525	
		2.3348	<u>STO 06</u>	2.3348	
		0.0026252	<u>STO 07</u>	0.0026252	
11	Calculate Pt_0 for $2 < d < 20 \mu m$		<u>A</u>	20.	0.002792262 20.
12	Recover and print				
	Pt_0 $0.1 < d < 20 \mu m$		<u>RCL 98</u>	.0088092652	
			<u>2nd Prt</u>		.0088092652

It is not useful to carry the integration past $20 \mu m$.

In summary:

$$Pt_0 = 0.0088,$$

$$E_0 = (1 - Pt_0) - 0.9912,$$

$$A/V = 0.7 \text{ cm}^2/\text{Acm}^3/\text{sec}, \text{ and}$$

$$T = 150^\circ\text{C}.$$

Sample printer output for example 4 is shown in Figure 4.

15.	PRT
4.	PRT
2.85176	PRT
1.06416	PRT
0.48567	PRT
0.7	PRT
0.25	PRT
4.	PRT
0.1	PRT
0.1	PRT
2.	PRT
0.1	PRT
0.7	PRT
.0060170031	PRT
2.	PRT
0.002792262	PRT
20.	PRT
.0088092652	PRT

Figure 4. PC-100A printer output for example 4--overall penetration through ESP.

Example 5

Determine the required specific collector area, A/V , required for an ESP to meet an emission standard of 0.02 mg/m^3 under given conditions.

Given:

Inlet loading	$= 2 \text{ mg/m}^3$
Mass median particle diameter	$= 15 \text{ }\mu\text{m}$
Geometric standard deviation	$= 4$
Dust electrical resistivity	$= 10^{11} \text{ ohm-cm}$
Normalized standard deviation of gas velocity distribution	$= 0.25$
Number of baffled sections	$= 4.0$
Fraction of particles that are reentrained and that bypass electrified region per section	$= 0.1$
Cold-side ESP T	$= 150^\circ\text{C}$

Solution:

$$\text{Required } Pt_0 = \frac{0.02}{1} = 0.01.$$

$$\text{Allowable current density, } j = 6.31 \times 10^{11} = 8.8 \text{ na/cm}^2.$$

Use a, b, c for 5 na/cm^2 .

Divide integration into two increments:

0.1 to $2 \text{ }\mu\text{m}$ with $\Delta d = 0.1$, and

2.0 to $20 \text{ }\mu\text{m}$ with $\Delta d = 1.0$.

First guess for $A/V = 1.0 \text{ cm}^2/\text{cm}^3/\text{sec}$ ($500 \text{ ft}^2/10^3 \text{ ACFM}$).

<u>Step</u>	<u>Procedure</u>	<u>Enter</u>	<u>Press</u>	<u>Display</u>	<u>Print</u>
1	Enter Card 1				
2	Enter all data	$d_g(15)$	<u>A</u>	15	15
		$\sigma_g(4)$	<u>RUN</u>	3.474924643	4
		$a(1.15987)$	<u>B</u>	1.15987	1.15987
		$b(0.3000)$	<u>RUN</u>	0.3	0.3
		$c(0.211888)$	<u>RUN</u>	0.211888	0.211888
		$A/V(1.0)$	<u>C</u>	-1.	1.
		$\sigma(0.25)$	<u>D</u>	0.018875	0.25
		$N_s(4.0)$	<u>E</u>	4.	4.
		$S(.1)$	<u>RUN</u>	0.1	0.1
		$d_i(0.1)$	<u>2nd A</u>	0.1	0.1
		$d_f(2.0)$	<u>RUN</u>	2.	2.
		$\Delta d(0.1)$	<u>RUN</u>	1.	0.1
					space
					1.
3	Enter Card 2				
4	Calculate Pt_0		<u>A</u>	2.	.0167131954
	$0.1 < d < 2.0 \mu m$				2.
	Penetration is already too high so there is no benefit in continuing the calculation.				
5	Increase A/V Enter Card 1				
	New A/V = 2	2.	<u>C</u>	-2.	2.
	Calculate constants		<u>2nd B'</u>	2.	space
	for Card 2				2.
6	Enter Card 2				
7	Calculate Pt_0 $0.1 < d < 2.0 \mu m$		<u>A</u>	2.	.0049972136
					2.

<u>Step</u>	<u>Procedure</u>	<u>Enter</u>	<u>Press</u>	<u>Display</u>	<u>Print</u>
8	Carry integration past $2.0 \mu\text{m}$				
9	Clear R_{19}	0.	<u>STO 19</u>	0.	
10	Store new d_i	2.	<u>STO 16</u>	2.	
11	Store new d_f	20.	<u>STO 17</u>	20.	
12	Store new Δd	1.	<u>STO 18</u>	1.	
13	Store new a, b, c for $b > 2.0 \mu\text{m}$				
		.94818	<u>STO 05</u>	.94818	
		.811698	<u>STO 06</u>	.811698	
		-.0003504	<u>STO 07</u>	.0003504	
14	Calculate Pt_0 $2. < d < 20 \mu\text{m}$		<u>A</u>	20.	.0025482646
					20.
15	Recover Pt_0 $0.1 < d < 20 \mu\text{m}$		<u>RCL 98 2nd Prt</u>	.0075454782	.0075454781
	This is too low. A/V needs to be decreased.				
16	Enter Card 1				
17	Enter new A/V	1.78	<u>C</u>	-1.78	1.78
18	Enter a, b, c for $d < 2.0 \mu\text{m}$				
		1.15987	<u>B</u>	1.15987	1.15987
		0.3	<u>RUN</u>	0.3	0.3
		0.211888	<u>RUN</u>	0.211888	0.211888
19	Enter d_i	0.1	<u>2nd A</u>	0.1	0.1
20	Enter d_f	2.0	<u>RUN</u>	2.0	2.
21	Enter Δd	0.1	<u>RUN</u>	1.78	0.1
					space
					1.78

<u>Step</u>	<u>Procedure</u>	<u>Enter</u>	<u>Press</u>	<u>Display</u>	<u>Print</u>
22	Enter Card 2				
23	Calculate Pt_0 $0.1 < d < 2 \mu m$		<u>A</u>	2.	.0064011292
					2.
24	Carry integration past $2.0 \mu m$				
25	Clear R_{19}	0	<u>STO 19</u>	0.	
26	Store new d_i	2.	<u>STO 16</u>	2.	
27	Store new d_f	20.	<u>STO 17</u>	20.	
28	Store new Δd	1.	<u>STO 18</u>	1.	
29	Store a, b, c for $d > 2.0 \mu m$				
		0.94818	<u>STO 05</u>	0.94818	
		0.811698	<u>STO 06</u>	0.811698	
		-0.0003504	<u>STO 07</u>	-0.0003504	
30	Calculate Pt_0 $2.0 < d < 20.0 \mu m$		<u>A</u>	20.	.0031990565
					20.
31	Recover and print Pt_0 $0.1 < d < 20.0 \mu m$		<u>RCL 98</u> <u>2nd</u> <u>Prt</u>	0.0096001857	0.0096001857

This is close enough to the desired penetration.

In Summary

$$Pt_0 = 0.01,$$

$$A/V = 1.78 \text{ cm}^2/\text{Acm}^3/\text{sec} (\sim 900 \text{ ft}^2/10^3 \text{ ACFM}),$$

$$j = 5 \text{ na/cm}^2, \text{ and}$$

$$T = 150^\circ\text{C}.$$

Printer output for example 5 is shown in Figure 5.

15.	PRT
4.	PRT
1.15987	PRT
0.3	PRT
0.211888	PRT
1.	PRT
0.25	PRT
4.	PRT
0.1	PRT
0.1	PRT
2.	PRT
0.1	PRT
1.	PRT
.0167131954	PRT
2.	PRT
2.	PRT
2.	PRT
.0049972136	PRT
2.	PRT
.0025482646	PRT
20.	PRT
.0075454781	PRT
1.78	PRT
1.15987	PRT
0.3	PRT
0.211888	PRT
0.1	PRT
2.	PRT
0.1	PRT
1.78	PRT
.0064011292	PRT
2.	PRT
.0031990565	PRT
20.	PRT
.0096001857	PRT

Figure 5. PC-100A printer output for example 5--specific collector area vs. ESP emission standard.

Example 6

Determine the effects of changing the size distribution parameters
from

$$d_g = 25 \mu\text{m}, \sigma_g = 4$$

to $d_g = 25 \mu\text{m}, \sigma_g = 3.$

for the given conditions.

Given:

$$A/V \text{ (cold-side)} = 0.7 \text{ cm}^2/\text{cm}^3/\text{sec}$$

$$\text{Current density} = 20 \text{ na/cm}^2$$

Normalized standard deviation of gas velocity

$$\text{distribution} = 0.25$$

$$\text{Number of baffled sections} = 4$$

$$\text{Fraction of particles that are reentrained and that} \\ \text{bypass electrified region per section} = 0.1$$

Solution:

Divide integration into two increments:

$$0.1 \text{ to } 2 \mu\text{m}, \text{ with } \Delta d = 0.1, \text{ and}$$

$$2 \text{ to } 20 \mu\text{m}, \text{ with } \Delta d = 1.0.$$

<u>Step</u>	<u>Procedure</u>	<u>Enter</u>	<u>Press</u>	<u>Display</u>	<u>Print</u>
1	Enter Card 1				
2	Enter all data	25	<u>A</u>	25.	25.
		4	<u>RUN</u>	3.474924643	4.
		2.85176	<u>B</u>	2.85176	2.85176
		1.06416	<u>RUN</u>	1.06416	1.06416
		0.48567	<u>RUN</u>	0.48567	0.48567
		0.7	<u>C</u>	-0.7	0.7
		0.25	<u>D</u>	0.018875	0.25

<u>Step</u>	<u>Procedure</u>	<u>Enter</u>	<u>Press</u>	<u>Display</u>	<u>Print</u>
		4	<u>E</u>	4.	4.
		0.1	<u>RUN</u>	.1	0.1
		0.1	<u>2nd A</u>	.1	0.1
		2.0	<u>RUN</u>	2.	2.0
		0.1	<u>RUN</u>	0.7	0.1
					space
					0.7
3	Enter Card 2				
4	Calculate Pt_0 $0.1 < d < 2.0 \mu m$ (calculation requires about 5 minutes)		<u>A</u>	2.	.0026480641
					2.
5	Continue integration past $2.0 \mu m$				
6	Clear R_{19}	0	<u>STO 19</u>	0	
7	Store new d_i	2.	<u>STO 16</u>	2.	
8	Store new d_f	20.	<u>STO 17</u>	20.	
9	Store new Δd	1.	<u>STO 18</u>	1.	
10	Enter new a, b, c for $d > 2 \mu m$				
		2.2525	<u>STO 05</u>	2.2525	
		2.3348	<u>STO 06</u>	2.3348	
		0.002652	<u>STO 07</u>	0.002652	
11	Calculate Pt_0 $2. < d < 20 \mu m$		<u>A</u>	20	.0019190628
					20.
12	Recover and print Pt_0 $0.1 < d < 20 \mu m$		<u>RCL 98 2nd</u> <u>Prt</u>	.0045671269	.0045671269

This is the overall penetration for $d_g = 25 \mu m$ and $\sigma_g = 4.$

For $d_g = 25 \mu\text{m}$ and $\sigma_g = 3$:

<u>Step</u>	<u>Procedure</u>	<u>Enter</u>	<u>Press</u>	<u>Display</u>	<u>Print</u>
1	Enter Card 1				
2	Enter data	25	<u>A</u>	25	25.
		3	<u>RUN</u>	2.753812626	3.
		2.85176	<u>B</u>	2.85176	2.85176
		1.06416	<u>RUN</u>	1.06416	1.06416
		0.48567	<u>RUN</u>	0.48567	0.48567
		0.1	<u>2nd A'</u>	0.1	0.1
		2.0	<u>RUN</u>	2.	2.
		0.1	<u>RUN</u>	0.7	0.1
					space
					0.7
3	Enter Card 2				
4	Calculate Pt_0 $0.1 < d < 2.0 \mu\text{m}$		<u>A</u>	2.	.0006880736
					2.
5	Continue integration past $2.0 \mu\text{m}$				
6	Clear R_{19}	0.	<u>STO 19</u>	0.	
7	Store new d_i	2.	<u>STO 16</u>	2.	
8	Store new d_f	20.	<u>STO 17</u>	20.	
9	Store new Δd	1.	<u>STO 18</u>	1.	
10	Store new a, b, c for $d > 2.0 \mu\text{m}$				
		2.2525	<u>STO 05</u>	2.2525	
		2.3348	<u>STO 06</u>	2.3348	
		0.002652	<u>STO 07</u>	0.002652	
11	Calculate Pt_0		<u>A</u>	20.	.001589385
	2. $< d < 20 \mu\text{m}$				20.
12	Recover and print		<u>RCL 98</u>	.0022774587	.0022774587
	Pt_0 $0.1 < d < 20 \mu\text{m}$		<u>2nd Prt</u>		

In summary:

$$T = 150^{\circ}\text{C},$$

$$A/V = 0.7 \text{ cm}^2/\text{Acm}^3/\text{sec},$$

$$\text{for } d_g = 25 \text{ and } \sigma_g = 4, \quad Pt_o = 0.0046, \text{ and}$$

$$\text{for } d_g = 25 \text{ and } \sigma_g = 3, \quad Pt_o = 0.0023.$$

Note the large effect that an increase in σ_g has on overall penetration.

Printer output for example 6 is shown in Figure 6.

Example 7

Determine penetration for the ESP in Example 4 for the case where dust resistivity is increased from 4×10^{10} ohm-cm to 10^{11} ohm-cm.

Given: All conditons, except dust resistivity, are as for example 4.

Solution:

$$\text{Allowable current density, } j = \frac{6.31 \times 10^{11}}{(10^{11})^{.987}} = 8.8 \text{ na/cm}^2.$$

Use a, b, c for 5 na/cm^2 .

Divide integration into two increments:

0.1 to 2.0 μm with $\Delta d = 0.1$, and

2.0 to 20 μm with $\Delta d = 1.0$.

25.	PRT
4.	PRT
2.85176	PRT
1.06416	PRT
0.48567	PRT
0.7	PRT
0.25	PRT
4.	PRT
0.1	PRT
0.1	PRT
2.	PRT
0.1	PRT
0.7	PRT
.0026480641	PRT
2.	PRT
.0019190628	PRT
20.	PRT
.0045671269	PRT
25.	PRT
3.	PRT
2.85176	PRT
1.06416	PRT
0.48567	PRT
0.1	PRT
2.	PRT
0.1	PRT
0.7	PRT
.0006880736	PRT
2.	PRT
0.001589385	PRT
20.	PRT
.0022774587	PRT

Figure 6. PC-100A printer output for example 6---changing ESP size distribution parameters.

<u>Step</u>	<u>Procedure</u>	<u>Enter</u>	<u>Press</u>	<u>Display</u>	<u>Print</u>
1	Enter Card 1				
2	Enter all data	15	<u>A</u>	15	15.
		4	<u>RUN</u>	3.474924643	4.
		1.15987	<u>B</u>	1.15987	1.15987
		0.3	<u>RUN</u>	0.3	0.3
		0.211888	<u>RUN</u>	0.211888	0.211888
		0.7	<u>C</u>	-0.7	0.7
		0.25	<u>D</u>	0.018875	0.25
		4	<u>E</u>	4.	4.
		0.1	<u>RUN</u>	0.1	0.1
		0.1	<u>2nd A</u>	0.1	0.1
		2.0	<u>RUN</u>	2.0	2.
		0.1	<u>RUN</u>	0.7	0.1
					space
					0.7
3	Enter Card 2				
4	Calculate Pt_0 $0.1 < d < 2.0 \mu m$	<u>A</u>	2.		.0251019171
					2.
5	Continue integration past $2.0 \mu m$				
6	Clear R_{19}	0.	<u>STO 19</u>	0.	
7	Store new d_i	2.	<u>STO 16</u>	2.	
8	Store new d_f	20.	<u>STO 17</u>	20.	
9	Store new Δd	1.	<u>STO 18</u>	1.	
10	Store new a, b, c for $d > 2.0 \mu m$				
11		0.94818	<u>STO 05</u>	0.94818	
12		0.811698	<u>STO 06</u>	0.811698	
13		-0.0003504	<u>STO 07</u>	-0.0003504	

<u>Step</u>	<u>Procedure</u>	<u>Enter</u>	<u>Press</u>	<u>Display</u>	<u>Print</u>
14	Calculate Pt_0 $2. < d < 20.0 \text{ } \mu\text{m}$		<u>A</u>	20.	.0273179683 20
15	Recover and print $Pt_0 \text{ } 0.1 < d < 20 \text{ } \mu\text{m}$		<u>RCL</u> <u>98</u> <u>2nd</u> <u>Prt</u>	.0524198854	.0524198854

In summary:

for $\rho = 4 \times 10^{10} \text{ ohm-cm}$, $Pt_0 = 0.008$, and

for $\rho = 10^{11} \text{ ohm-cm}$, $Pt_0 = 0.052$.

Printer output for example 7 is shown in Figure 7.

Example 8

Determine the effect of increasing the normalized standard deviation of the gas flow distribution in Example 4 from 0.25 to 0.5.

Given: All conditions, except normalized standard deviation of the gas flow distribution, are as for example 4.

Solution:

Divide integration into two increments:

0.1 to 2.0 μm with $\Delta d = 0.1 \text{ } \mu\text{m}$, and

2.0 to 20 μm with $\Delta d = 1.0 \text{ } \mu\text{m}$.

15.	PRT
4.	PRT
1.15987	PRT
0.3	PRT
0.211888	PRT
0.7	PRT
0.25	PRT
4.	PRT
0.1	PRT
0.1	PRT
2.	PRT
0.1	PRT
0.7	PRT
.0251019171	PRT
2.	PRT
.0273179683	PRT
20.	PRT
.0524198854	PRT

Figure 7. PC-100A printer output for example 7--ESP penetration vs. dust resistivity.

<u>Step</u>	<u>Procedure</u>	<u>Enter</u>	<u>Press</u>	<u>Display</u>	<u>Print</u>
1	Enter Card 1				
2	Enter all data	15	<u>A</u>	15	15.
		4	<u>RUN</u>	3.474924643	4.
		2.85176	<u>B</u>	2.85176	2.85176
		1.06416	<u>RUN</u>	1.06416	1.06416
		0.48567	<u>RUN</u>	0.48567	0.48567
		0.7	<u>C</u>	-0.7	0.7
		0.5	<u>D</u>	0.03775	0.5
		4.	<u>E</u>	4.	4.
		0.1	<u>RUN</u>	0.1	0.1
		0.1	<u>2nd A'</u>	0.1	0.1
		2.0	<u>RUN</u>	2.0	2.
		0.1	<u>RUN</u>	0.7	0.1
					space
					0.7
3	Enter Card 2				
4	Calculate Pt_0 0.1 < d < 2.0 μm		<u>A</u>	2.	.0088151441 2.
5	Continue integration past 2.0 μm				
6	Clear R_{19}	0.	<u>STO 19</u>	0.	
7	Store new d_i	2.	<u>STO 16</u>	2.	
8	Store new d_f	20.	<u>STO 17</u>	20.	
9	Store new Δd	1.	<u>STO 18</u>	1.	
10	Store new a, b, c for d > 2.0 μm				
		2.2525	<u>STO 05</u>	2.2525	
		2.3348	<u>STO 06</u>	2.3348	
		0.002652	<u>STO 07</u>	0.002652	

<u>Step</u>	<u>Procedure</u>	<u>Enter</u>	<u>Press</u>	<u>Display</u>	<u>Print</u>
11	Calculate Pt_0				
	2. < d < 20 μm		<u>A</u>	20.	.0088824589
					20.
12	Recover and print		<u>RCL</u> <u>98</u>	.017697603	
	Pt_0 0.1 < d < 20 μm		<u>2nd</u> <u>Prt</u>		0.017697603

In summary:

for $\sigma = 0.5$, $Pt_0 = 0.018$, and

for $\sigma = 0.25$, $Pt_0 = 0.0088$.

This example emphasizes the need for uniform gas velocity distribution in a high efficiency ESP.

Printer output for example 8 is in Figure 8.

15.	PRT
4.	PRT
2.85176	PRT
1.06416	PRT
0.48567	PRT
0.7	PRT
0.5	PRT
4.	PRT
0.1	PRT
0.1	PRT
2.	PRT
0.1	PRT
0.7	PRT
.0088151441	PRT
2.	PRT
.0088824589	PRT
20.	PRT
0.017697603	PRT

Figure 8. PC-100A printer output for example 8--changing normalized standard deviation of ESP gas flow distribution.

CAUTIONS ON USING SR-52 PROGRAM RESULTS

The SR-52 program is based on results calculated using the EPA/SoRI ESP computer model for typical ESP used to collect fly ash. Thus, the calculated results are most accurate when the dust concentrations, particle size distributions, and voltage/current relationships are close to those used in the computer model calculations. Even in those cases the SR-52 results will predict values of penetration somewhat higher than those predicted by the computer model for large specific collector area ESP.

The correction factors for non-ideal effects have not been subjected to rigorous experimental evaluation. These correction factors, however, in combination with the rest of the model do give useful results which are in line with available experimental data.

Note that although the absolute accuracy of the SR-52 calculations may not be high when conditions other than those used in the computer model calculations are of interest, the trends predicted by the SR-52 program are still correct and provide useful information.

REFERENCES

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2. Gooch, J. P., McDonald, J. R., and Oglesby, S., Jr., "A Mathematical Model of Electrostatic Precipitation," EPA-650/2-75-037 (NTIS PB 246-188/AS), April 1975.
3. Calvert S., "Source Control by Liquid Scrubbing," Chapter 46 in Air Pollution. A. Stern ed. Academic Press, 1968.
4. Calvert, S., Yung, S., and Barbarika, H., "Venturi Scrubber Performance Model," EPA-600/2-77-172 (NTIS PB 271-515/AS), August 1977.
5. Hall, H. J., "Trends in Electrical Energization of Electrostatic Precipitators." Presented at the Electrostatic Precipitator Symposium, February 23-25, 1971. Birmingham, Alabama.

APPENDIX A

USER INSTRUCTIONS AND PROGRAM LISTING FOR VENTURI SCRUBBER PROGRAM

USER INSTRUCTIONS

Enter Card 1, sides A and B. Enter data as follows:

<u>Enter</u>	<u>Press</u>	<u>Display</u>
T °C	<u>A</u>	T°K x 10 ⁻⁴
f (usually 0.5)	<u>RUN</u>	f
d _g μm	<u>RUN</u>	1.01
σ _g	<u>RUN</u>	7.00
d _i μm	<u>RUN</u>	6.00
d _f μm	<u>RUN</u>	5.00
Δd μm (if known)	<u>RUN</u>	4.00
<u>2nd stfl 1</u> (if number n of steps n known)	<u>RUN</u>	4.00
ρ _L gm/cm ³	<u>RUN</u>	3.00
L/G m ³ /m ³	<u>RUN</u>	2.00
u _G cm/sec	<u>RUN</u>	1.00
μ poise	<u>RUN</u>	0.00
ρ _p gm/cm ³	<u>RUN</u>	Δp cm water
0	<u>RUN</u>	0

Enter Card 2 and press A. Display d_f.

Title Venturi Scrubber Card 1
 Programmer L. E. Sparks

Page 1 of 2
 Date _____

Loc	Code	Key	Comments	Loc	Code	Key	Comments	Loc	Code	Key	Comments	Labels
000 +22	46	LBL			54	)			01	1		A Main
	10	E ⁷⁸			54	)			08	8		B
	98	pri		040 +22	98	pri			75	-		C
	53	(			56	rtn			43	RCL		D Drop Jan
	36	IND			46	LBL		080 +22	00	0		E
005 +22	42	STO			11	A			00	0		A'
	00	0			99	pri			95	=		B'
	00	0		045 +22	98	pri			80	if pos		C'
	65	X			85	+			87	1'		D'
	01	1			02	2		085 +22	46	LBL		E'
010 +22	44	SYM			07	7			13	C		Registers
	00	0			03	3			14	D		00
	00	0		050 +22	95	=			65	X		01
	54	)			52	EE			02	2		02
	56	rtn			94	+/-		090 +22	55	÷		03
015 +22	46	LBL			04	4			05	5		04
	14	D			42	STO			05	5		05
	53	(		055 +22	00	0			65	X		06
	05	5			03	3			43	RCL		07
	00	0			81	HLT		095 +22	01	1		08
020 +22	55	÷			98	pri			05	5		09
	43	RCL			42	STO			65	X		10
	01	1		060 +22	00	0			43	RCL		11
	06	6			04	4			01	1		12
	85	+			81	HLT		100 +22	04	4		13
025 +22	09	9			98	pri			65	X		14
	01	1			42	STO			43	RCL		15
	93	.		065 +22	00	0			01	1		16
	08	8			08	8			06	6		17
	65	X			01	1		105 +22	55	÷		18
030 +22	53	(			00	0			43	RCL		19
	43	RCL			42	STO			01	1		Flags
	01	1		070 +22	00	0			07	7		0
	05	5			00	0			95	=		1
	45	4'			46	LBL		110 +22	42	STO		2
035 +22	01	1			87	1'			00	0		3
	93	.			81	HLT						4
	05	5		075 +22	10	E'						

Title Venturi Scrubber Card 1 Page 2 of 2
 Programmer L.E. Sparks Date _____

Loc	Code	Key	Comments	Loc	Code	Key	Comments	Loc	Code	Key	Comments	Labels
000 112	07	7			01	1			95	=		A
	43	RCL			00	0			94	+/-		B
	01	1		040 152	23	ln π			55	$\div$		C
	06	6			65	X			43	RCL		D
	65	X			53	(		080 192	01	1		E
005 117	43	RCL			02	2			03	3		A'
	01	1			65	X			95	=		B'
	08	8		045 157	59	π^*			42	STO		C'
	55	$\div$			54	)			01	1		D'
	43	RCL			30	$\sqrt{x}^*$		085 197	03	3		E'
010 122	01	1			95	=			22	INV		Registers
	07	7			42	STO			50	st flg *		00
	55	$\div$		050 162	01	1			01	1		01
	09	9			00	0			46	LBL *		02
	52	EE			50	st flg *		090 202	16	A' *		03
015 127	08	8			02	2			08	8		04
	55	$\div$			46	LBL *			93	.		05
	14	D		055 167	38	D.Ms *			02	2		06
	95	=			00	0			04	4		07
	42	STO			42	STO		095 207	52	EE		08
020 132	00	0			01	1			94	+/-		09
	02	2			09	9			04	4		10
	60	if flg *		060 172	43	RCL			65	X		11
	02	2			01	1			43	RCL		12
	38	D.Ms *			01	1		100 212	01	1		13
025 137	43	RCL			42	STO			06	6		14
	01	1			00	0			40	π^*		15
	00	0		065 177	01	1			65	X		16
	23	ln π			60	if flg *			43	RCL		17
	40	π^*			01	1		105 217	01	1		18
030 142	65	X			69	9' *			05	5		19
	02	2			16	A' *			95	=		Flags
	94	+/-		070 182	46	LBL *			99	pap *		0
	95	=			69	9' *			98	pri *		1
	42	STO			75	-		110 222	99	pap *		2
035 147	00	0			43	RCL			81	HLT		3
	09	9			01	1						4
	43	RCL		075 187	02	2						

Loc	Code	Key	Comments	Loc	Code	Key	Comments	Loc	Code	Key	Comments	Labels
000 442	46	LBL*			80	if pos*			95	=		A
	10	E'*			89	3'*			98	pri*		B
	01	1		040 152	01	1			44	SUM		C
	44	SUM			46	LBL*			09	9		D
	00	0			77	4'*		060 102	08	8		E
005 447	00	0			95	=			43	RCL		A'
	36	IND*			44	SUM			01	1		B'
	43	RCL		045 157	01	1			01	1		C'
	00	0			09	9			98	pri*		D'
	00	0			43	RCL		085 197	43	RCL		E'
010 422	56	rtn*			01	1			01	1		Registers
	46	LBL*			03	3			02	2		00
	11	A		050 162	44	SUM			98	pri*		01
	00	0			00	0			81	HLT		02
	42	STO			01	1		090 202	46	LBL*		03
015 427	00	0			41	GTO			15	E		04
	00	0			11	A			53	(		05
	13	C		055 167	46	LBL*			41	GTO		06
	15	E			88	2'*			19	D'*		07
	65	X			93	.		095 207	46	LBL*		08
020 420	14	D			05	5			37	D.M.s*		09
	65	X			41	GTO			65	X		10
	53	(		060 172	77	4'*			10	E'*		11
	10	E'*			46	LBL*			54	)		12
	75	-			89	3'*		100 212	22	INV		13
025 427	43	RCL			93	.			23	int		14
	00	0			05	5			56	rtn*		15
	01	1		065 177	95	=			46	LBL*		16
	54	)			44	SUM			19	D'*		17
	90	ifo*			01	1		105 217	53	(		18
030 442	88	2'*			09	9			53	(		19
	53	(			43	RCL			01	1		Flags
	43	RCL		070 182	01	1			93	.		0
	00	0			09	9			04	4		1
	01	1			65	X		110 222	65	X		2
035 447	75	-			43	RCL			53	(		3
	10	E'*			01	1						4
	54	)		075 187	03	3						

Title Venturi Scrubber Card 2
 Programmer L.E. Sparks

Page 2 of 2
 Date _____

Loc	Code	Key	Comments	Loc	Code	Key	Comments	Loc	Code	Key	Comments	Labels
~~000~~ 112	10	E'*			55	÷			06	6		A
	55	÷			43	RCL			10	E'*		B
	93	.		~~046~~ 152	00	0			85	+		C
	07	7			01	1			93	.		D
	54	)			65	X		~~006~~ 192	07	7		E
~~005~~ 117	23	ln t			53	(			54	)		A'
	85	+			02	2			42	STO		B'
	93	.		~~045~~ 157	93	.			00	0		C'
	04	4			07	7			05	5		D'
	09	9			09	9		~~005~~ 197	56	rt n*		E'
~~046~~ 122	55	÷			85	+			46	LBL*		Registers
	43	RCL			93	.			14	D		30
	00	0		~~060~~ 162	08	8			53	(		01
	05	5			09	9			53	(		02
	75	-			04	4		~~000~~ 202	53	(		03
~~045~~ 127	43	RCL			65	X			43	RCL		04
	00	0			53	(			00	0		05
	05	5		~~066~~ 167	93	.			01	1		06
	54	)			02	2			55	÷		07
	55	÷			04	4		~~005~~ 207	10	E'*		08
~~000~~ 132	10	E'*			07	7			54	)		09
	54	)			65	X			23	ln t		10
	41	GTO		~~000~~ 172	43	RCL			40	x ² *		11
	37	D.M.s*			00	0			55	÷		12
	46	LBL*			01	1		~~100~~ 212	10	E'*		13
~~005~~ 137	13	C			55	÷			54	)		14
	53	(			43	RCL			22	INV		15
	10	E'*		~~065~~ 177	00	0			23	ln t		16
	40	x ² *			03	3			55	÷		17
	65	X			94	+/-		~~106~~ 217	43	RCL		18
~~030~~ 142	10	E'*			54	)			00	0		19
	65	X			22	INV			01	1		Flags
	53	(		~~070~~ 182	23	ln t			55	÷		0
	01	1			54	)			10	E'*		1
	85	+			54	)		~~110~~ 222	54	)		2
~~035~~ 147	02	2			65	X			56	rt n*		3
	65	X			42	STO						4
	10	E'*		~~075~~ 187	00	0						

APPENDIX B

USER INSTRUCTIONS AND PROGRAM LISTING FOR ESP PROGRAM

USER INSTRUCTIONS

Enter Card 1, sides A and B. Enter data as follows:

<u>Enter</u>	<u>Press</u>	<u>Display</u>
$d_g \text{ } \mu\text{m}$	<u>A</u>	d_g
σ_g	<u>RUN</u>	σ_g
a	<u>B</u>	a
b	<u>RUN</u>	b
c	<u>RUN</u>	c
$A/V \text{ cm}^2/\text{Acm}^3/\text{sec}$	<u>C</u>	$-A/V^{**}$
or $A/V \text{ ft}^2/10^3 \text{ ACFM}$	<u>2nd stf1 1 C</u>	$-A/V \text{ cm}^2/\text{Acm}^3/\text{sec}$
σ	<u>D</u>	σ
N_s	<u>E</u>	N_s
S	<u>RUN</u>	S
$d_i \text{ } \mu\text{m}$	<u>2nd A'</u>	d_i
$d_f \text{ } \mu\text{m}$	<u>RUN</u>	d_f
$\Delta d \text{ } \mu\text{m}$	<u>RUN</u>	Δd
or n (number of steps)	<u>2nd stflg 2 RUN</u>	Δd

Enter Card 2. Press A. Display d_f .

Recover Pt_0 by pressing RCL 98.

²
** A/V in $\text{cm}^2/\text{Acm}^3/\text{sec}$ is displayed because the program uses A/V in the calculations.

Title F.S.P. Card 1
 Programmer L. E. Sparks

Page 1 of 1
 Date _____

Loc	Code	Key	Comments	Loc	Code	Key	Comments	Loc	Code	Key	Comments	Labels
033 332	46	LBL			09	9			01	1		A
	10	E'*			65	X			95	=		B
	36	IND		040 152	53	(			60	ifflg*		C
	42	STO			02	2			01	1		D
	00	0			65	X		080 102	87	1'*		E
005 337	00	0			59	11*			10	E'*		A'
	65	X			54	)			56	rtu*		B'
	01	1		045 157	30	12*			46	LBL		C
	44	SUM			95	=			87	1'*		D'
	00	0			10	E'*		085 107	65	X		E
010 102	00	0			56	rtu*			01	1		Registers
	95	=			46	LBL			93	.		00
	56	rtu*		050 162	12	B			09	9		01
	46	LBL			98	prt*			06	6		02
	11	H			65	X		090 202	09	9		03
015 122	98	prt*			05	5			52	EE		04
	65	X			42	STO			94	+/-		05
	02	2		055 167	00	0			03	3		06
	42	STO			00	0			95	=		07
	00	0			01	1		095 207	10	E'*		08
020 102	00	0			95	=			56	rtu*		09
	01	1			10	E'*			46	LBL		10
	95	=		060 172	81	HLT			14	D		11
	10	E'*			98	prt*			98	prt*		12
	81	HLT			10	E'*		100 212	42	STO		13
025 132	98	prt*			81	HLT			01	1		14
	23	prt*			98	prt*			09	9		15
	42	STO		065 172	10	E'*			01	1		16
	01	1			56	rtu*			01	1		17
	09	9			46	LBL		105 217	42	STO		18
030 142	40	1'*			13	C			00	0		19
	65	X			98	prt			00	0		Flags
	02	2		070 182	94	+/-			43	RCL		0
	95	=			65	X			01	1		1
	94	+/-			09	9		110 222	09	9		2
035 142	10	E'*			42	STO			45	1'*		3
	43	RCL			00	0						4
	01	1		075 182	00	0						

Title ESP Card 1
 Programmer L. E. Sparks

Page 2 of 2
 Date _____

Loc	Code	Key	Comments	Loc	Code	Key	Comments	Loc	Code	Key	Comments	Labels
112	01	1			06	6			17	B'*		A
	93	.			42	STO			00	0		B
	07	7		152	00	0			42	STO		C
	08	8			00	0			01	1		D
	06	6			01	1		192	09	9		E
117	95	=			95	=			42	STO		A'
	65	X			10	E'*			09	9		B'
	93	.		157	81	HLT			08	8		C'
	07	7			98	prt*			43	RCL		D
	06	6			10	E'*		197	01	1		E'
122	06	6			81	HLT			06	6		Registers
	95	=			98	prt*			42	STO		00
	10	E'*		162	10	E'*			00	0		01
	43	RCL			60	itflg*			01	1		02
	01	1			02	2		202	22	INV		03
127	09	9			88	2'*			50	stflg*		04
	65	X			17	B'*			01	1		05
	93	.		167	46	LBL			22	INV		06
	00	0			88	2'*			50	stflg*		07
	07	7			43	RCL		207	02	2		08
132	05	5			01	1			22	INV		09
	05	5			07	7			52	EE		10
	95	=		172	75	-			99	pap*		11
	10	E'*			43	RCL			43	RCL		12
	56	rtu*			01	1		212	00	0		13
137	46	LBL			06	6			09	9		14
	15	E			95	=			94	+/-		15
	98	prt*		177	55	÷			98	prt*		16
	10	E'*			43	RCL			99	pap*		17
	81	HLT			01	1		217	81	HLT		18
142	98	prt*			08	8						19
	10	E'*			95	=						Flags
	56	rtu*		182	42	STO						0
	46	LBL			01	1						1
	16	A'*			08	8		222				2
147	98	prt*			98	prt*						3
	65	X			17	B'*						4
	01	1		187	46	LBL						

Title ESP Card 2
 Programmer L.E. Sparks

Page 1 of 2
 Date _____

Loc	Code	Key	Comments	Loc	Code	Key	Comments	Loc	Code	Key	Comments	Labels
000 322	46	LBL			01	I			54	)		A
	10	E' *			56	rtn *			19	D' *		B
	53	(		040 322	46	LBL			65	X		C
	36	IND			14	D			10	E' *		D
	43	RCL			53	(		080 322	54	)		E
005 322	00	O			53	(			22	INV		A'
	00	O			53	(			23	lnx		B'
	65	X		045 322	10	E' *			19	D' *		C'
	53	(			55	÷			53	(		D'
	01	I			10	E' *		085 322	43	RCL		E'
010 322	44	S4M			54	)			00	O		Registers
	00	O			23	lnx			08	8		00
	00	O		050 322	40	x ² *			55	÷		01
	54	)			55	÷			53	(		02
	01	I			10	E' *		090 322	01	I		03
015 322	54	)			54	)			85	+		04
	56	rtn *			22	INV			10	E' *		05
	46	LBL		055 322	23	lnx			65	X		06
	19	D' *			55	÷			53	(		07
	53	(			18	C' *		095 322	01	I		08
020 322	36	IND			55	÷			75	-		09
	42	STO			10	E' *			17	B' *		10
	00	O		060 322	54	)			54	)		11
	00	O			56	rtn *			85	+		12
	65	X			46	LBL		100 322	10	E' *		13
025 322	53	(			15	E			65	X		14
	01	I			53	(			53	(		15
	44	S4M		065 322	53	(			17	B' *		16
	00	O			10	E' *			20	1/2 *		17
	00	O			85	+		105 322	23	lnx		18
030 322	54	)			18	C' *			54	)		19
	01	I			65	X			54	)		Flags
	54	)		070 322	10	E' *			55	÷		0
	56	rtn *			85	+			53	(		1
	46	LBL			18	C' *		110 322	17	B' *		2
035 322	18	C' *			40	x ² *			23	lnx		3
	43	RCL			65	X						4
	00	O		075 322	10	E' *						

Title ESP Card 2
 Programmer L. E. Sparks

Page 2 of 2
 Date _____

Loc	Code	Key	Comments	Loc	Code	Key	Comments	Loc	Code	Key	Comments	Labels
~~110~~ 112	55	÷			46	LBL			08	8		A
	10	E'*			11	A			44	SYM		B
	55	÷		~~150~~ 152	01	1			00	0		C
	53	(			42	STO			01	1		D
	10	E'*			00	0		~~190~~ 192	25	clr		E
~~117~~ 117	85	+			00	0			41	GTO		A'
	53	(			53	(			11	A		B'
	01	1		~~157~~ 157	53	(			46	LBL		C'
	75	-			14	D			89	2'*		D'
	43	RCL			65	X		~~196~~ 197	93	.		E'
~~120~~ 122	01	1			15	E			05	5		Registers
	04	4			54	)			41	GTO		00
	54	)		~~160~~ 162	65	X			77	4'*		01
	65	X			53	(			46	LBL		02
	17	B'*			18	C'*		~~202~~ 202	89	3'*		03
~~125~~ 127	45	4'*			75	-			93	.		04
	10	E'*			10	E'*			05	5		05
	43	RCL		~~167~~ 167	54	)			54	(		06
	01	1			90	if 0*			44	SYM		07
	03	3			88	2'*		~~207~~ 207	01	1		08
~~130~~ 132	20	1/x*			53	(			09	9		09
	54	)			18	C'*			53	(		10
	23	ln t		~~172~~ 172	75	-			10	E'*		11
	54	)			10	E'*			10	E'*		12
	65	X			54	)		~~212~~ 212	X	X		13
~~137~~ 137	43	RCL			90	if 0*			43	RCL		14
	00	0			89	3'*			01	1		15
	09	9		~~177~~ 177	80	if pos*			08	8		16
	54	)			89	3'*			54	)		17
	22	INV			01	1		~~217~~ 217	98	pri*		18
~~142~~ 142	23	ln t			46	LBL			44	SYM		19
	56	rtn*			77	4'*			09	9		Flags
	46	LBL		~~182~~ 182	54	)			08	8		0
	17	B'*			44	SYM			18	C'*		1
	43	RCL			01	1		~~222~~ 222	98	pri*		2
~~147~~ 147	01	1			09	9			81	HLT		3
	00	0			43	RCL						4
	56	rtn*		~~187~~ 187	01	1						